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Frost Resistance of Cover and Liner Materials for Landfills and Hazardous Waste Sites

Edwin J. Chamberlain, Allan E. Erickson,
and Craig H. Benson

December 1997

Abstract: The common method of preventing the contamination of groundwater by landfills and hazardous waste is to encapsulate the waste material in a compacted clay liner and cover system. The frost resistance of compacted clay in landfills has been the subject of controversy for many years. Laboratory studies have frequently shown that freezing and thawing significantly increase the hydraulic conductivity of compacted clay soils. However, there has not been any corroborating field evidence. This study more closely examines this problem, and identifies cover and liner materials that would be frost resistant to increase construction productivity and save costs under a CPAR (Construction Productivity Advancement Research) cooperative agreement between CRREL and five private companies. The effects of freezing and thawing on the hydraulic conductivity of two compacted natural clay soils, one compacted sand–bentonite mixture, and three geosynthetic clay liners (GCLs) were examined. Both field and laboratory tests were performed on these materials. The field test site consisted of five test pads (four of clay and one of sand–bentonite), and nine test pans containing three different GCLs. Results showed that freeze–thaw caused large increases (greater than 1000×) in hydraulic conductivity in compacted natural clay, but little measurable change in hydraulic conductivity of the GCLs or the sand–bentonite mixture. GCLs and sand–bentonite mixtures are suitable frost resistant substitutes for compacted clay soils. Considerable cost savings can result if compacted clay soils are replaced with GCLs or sand–bentonite mixtures.

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PREFACE

This report was prepared by Edwin J. Chamberlain, Research Civil Engineer, Applied Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory; Allan E. Erickson, Civil Engineer, CH2M Hill, Inc., Milwaukee, Wisconsin; and Craig H. Benson, Professor, Department of Civil and Environmental Engineering, University of Wisconsin, Madison, Wisconsin.

This study was conducted under the U.S. Army Corps of Engineers (USACE) *Construction Productivity Advancement Research* (CPAR) Program. The authority for this program is given in Section 7 of the *Water Resources Development Act of 1988*, P.L. 100-676 33 U.S.C 2313, and the *Stevenson-Wydler Technology Innovation Act of 1980*, as amended, 15 U.S.C. 37102a. The CPAR Program allows USACE to enter into cooperative research and development agreements with construction industry partners to do cost-shared, collaborative work with the goal of improving construction productivity and efficiency.

The project was entitled *Construction of Soil Liners for Landfills, Hazardous Waste Containment and Disposal Sites in Cold Regions*. The work was conducted under a cooperative agreement by CRREL, CH2M Hill, Inc., WMX Inc., James Clem Corporation, Colloid Environmental Technologies Company, and Gundle Lining Systems, Inc. The University of Wisconsin and Oregon State University contributed to the work under contracts with CH2M Hill and CRREL, respectively. The work was conducted between January 1990 and October 1995. The USACE Technical Monitor was Gregory Hughes.

Dr. Maria Porebska, University of Krakow and visiting Fulbright Scholar at CRREL, Pamela Chin, John Bodet, Jeffrey Stark, and Dr. Patrick Black are gratefully acknowledged for their assistance with the test program at CRREL. Assistance from the industrial partners on this CPAR project with construction and financial aspects of test pad construction is also gratefully acknowledged: A special note of appreciation is expressed to the employees of the Parkview Landfill in Menominee Falls, Wisconsin, where the field study was conducted. Appreciation is also expressed to Xiaodong Wang, Geotechnical Laboratory Manager at the University of Wisconsin, and Jason Krau and Tarek Abichou, students at the University of Wisconsin.

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EXECUTIVE SUMMARY

The common method of preventing the contamination of groundwater by landfill and hazardous waste is to encapsulate the waste material in a compacted clay liner and cover system. The Environmental Protection Agency has proposed guidelines for the design of disposal sites under their jurisdiction. These guidelines generally call for a system of components, including compacted clay layers and geosynthetic membranes, encapsulating the waste material. The EPA usually requires that the hydraulic conductivity of the compacted clay be less than 1×10^{-7} cm/s and that the clay be protected from freezing.

The frost resistance of compacted clay covers and liners for landfills and hazardous waste sites has been the subject of controversy for many years. Laboratory studies have frequently shown that freezing and thawing significantly increase the hydraulic conductivity of compacted clay soils. However, there has not been any corroborating field evidence. Moreover, when "undisturbed" samples from clay liners, which have frozen and thawed in the field, have been examined in the laboratory, little or no change in hydraulic conductivity has been observed. Nonetheless, the persistent laboratory evidence has led the EPA and many other regulatory agencies to set guidelines requiring frost protection for compacted clay covers and liners. The cost and questionable necessity for the frost protection have resulted in considerable controversy among regulators, designers, and owners of landfills.

This study more closely examines this problem. Since the overwhelming evidence in the literature convinced us that careful study in the laboratory and in the field would confirm that frost action was a problem for compacted clay soils, we decided to also look at alternatives to the standard clay cover and liner materials. The ultimate purpose of this study was to identify cover and liner materials that would be frost resistant, or find a way to make frost-susceptible materials frost resistant, and at the same time increase construction productivity and save costs.

We developed a field and laboratory program under a CPAR (Construction Productivity Advancement Research) cooperative agreement between CRREL and five private companies involved in the waste management field. The lead in the private sector was taken by CH2M Hill, Inc., a leading consulting engineering firm in the environmental geotechniques field. The other partners included WMX, Inc., one of the largest owners and operators of landfills in the U.S., and James Clem Corporation, Colloid Environmental Technologies Company, and Gundle Lining Systems, Inc., three companies that produce GCL (geosynthetic clay liner) systems and promote their use as alternatives to compacted clay soils.

We examined the effects of freezing and thawing on the hydraulic conductivity of two compacted natural clay soils, one compacted sand–bentonite mixture, and three GCLs. These materials were tested both in the field and laboratory. A field test site was constructed at a WMX, Inc., landfill near Milwaukee, Wisconsin. The field test site consisted of five test pads (four of clay and one of sand–bentonite), and nine test pans containing three different GCLs.

Results of the investigation showed that freeze–thaw caused large increases (greater than 1000×) in the hydraulic conductivity of compacted natural clay, but little measurable change in the hydraulic conductivity of the GCLs or the sand–bentonite mixture. This study also showed that past soil sampling and laboratory testing practices were probably errant in their findings that freezing and thawing did not damage compacted clay soils. Test samples of clay taken with the standard thin-walled tube samplers showed little or no change in hydraulic conductivity after freezing and thawing, while carefully carved block samples and samples taken while the clay was frozen with a special coring auger showed the large increases in hydraulic conductivity after freezing and thawing.

The findings show that GCLs and sand–bentonite mixtures are suitable frost-resistant substitutes for compacted clay soils. The cost of a GCL liner in place is approximately the same as 2 ft (0.6 m) of compacted clay, and a sand–bentonite liner may cost a little more, so there are little cost savings associated just with the material purchase and placement. However, considerable cost savings can result if compacted clay soils are replaced with GCLs or sand–bentonite mixtures. These

result from the elimination of the cost of the construction of the frost protection layer and the added value of the increased storage space resulting from the elimination of the frost protection and compacted clay layers. In much of the highly populated areas of the U.S., these cumulative cost savings can exceed $200,000 per acre or $4,000,000 for a typical 20-acre disposal site ($494,000/ha or $4,000,000 for an 8-ha site) and represent 3 to 16% of the fixed costs.

This report chronicles the work accomplished and the findings. Appropriate laboratory freezing test methods are discussed, as are the field sampling methods. Contour maps are provided to show the thickness of frost protection required for compacted clay covers. The potential cost savings obtainable using GCLs and sand–bentonite in place of clay are also given.

Frost Resistance of Cover and Liner Materials for Landfills and Hazardous Waste Sites

EDWIN J. CHAMBERLAIN, ALLAN E. ERICKSON, AND CRAIG H. BENSON

INTRODUCTION

The common method of preventing the contamination of groundwater by landfill and hazardous waste is to encapsulate the waste material in a compacted clay liner and cover system. The Environmental Protection Agency has proposed guidelines for the design of disposal sites under their jurisdiction. These guidelines generally call for a system of components that includes compacted clay layers and geosynthetic membranes encapsulating the waste material. The EPA usually requires that the hydraulic conductivity of the compacted clay be less than 1×10^{-7} cm/s, and that the clay be protected from freezing.

The frost resistance of compacted clay covers and liners for landfills and hazardous waste sites has been the subject of controversy for many years. Laboratory studies have frequently shown that freezing and thawing significantly increase the hydraulic conductivity of compacted clay soils. However, there has not been any corroborating field evidence. Moreover, when "undisturbed" samples from clay liners, which have frozen and thawed in the field, have been examined in the laboratory, little or no change in hydraulic conductivity has been observed. Nonetheless, the persistent laboratory evidence of freezing and thawing has led the EPA and other regulatory agencies to set guidelines requiring frost protection for compacted clay covers and liners.

Our intent here was to more closely examine this problem. Since it appeared that careful study would confirm that frost action was a problem for compacted clay soils, we decided to also look at alternatives to the standard clay cover and liner materials. The purpose of this study was to identify cover and liner materials or conditions that would be frost resistant and at the same time increase productivity and save costs.

We developed a field and laboratory program under a U.S. Army Corps of Engineers CPAR (Construction Productivity Advancement Research) cooperative agreement between CRREL and five private companies involved in the waste management field. The CPAR program was implemented to advance the productivity of the U.S. construction industry. The U.S. Army's research laboratories were to join forces with private industry to conduct research on issues important to the Army and the Nation. The lead in the private sector was taken by CH2M Hill, a leading consulting engineering firm in the environmental geotechniques field. The other partners were WMX, Inc., one of the largest owners and operators of landfills in the U.S., and James Clem Corporation, Colloid Environmental Technologies Company, and Gundle Lining Systems, Inc., three companies that produce geosynthetic soil layer systems and promote their use as alternatives to compacted clay soils.

This report describes a study that examined how freezing and thawing affects the hydraulic conductivity of two compacted natural clay soils, one compacted sand–bentonite mixture, and three geosynthetic clay liners (GCLs). The clay soils were typical of those used for landfill covers and liners, with low and medium plasticities. The bentonite in the sand–bentonite mixture is a highly swelling clay that hydrates on exposure to water and plugs the channels in the sand. GCLs are made up of one or more geosynthetic material and a thin layer of bentonite clay. The bentonite in

the GCLs works in much the same way as in the sand–bentonite mixture. In this case, the bentonite is in a continuous layer, held in place by the geosynthetics, that hydrates and forms a barrier to moisture flow.

The goals of the study were to improve the understanding of how freeze–thaw affects these materials, to improve the design and construction process, and to reduce costs and increase productivity. The scope of the project was developed to gather data to be used in answering the following questions:

- Do freezing and thawing increase the hydraulic conductivity of compacted clay soils, sand–bentonite mixtures, or GCLs under natural conditions?
- Do laboratory hydraulic conductivity tests accurately predict the hydraulic conductivity of clay liners and covers in the field after freezing and thawing?
- If laboratory tests can be used to predict the hydraulic conductivity in compacted clay covers and liners after freezing and thawing, then why have past studies failed to do this and what can be done to improve the predictive methods?
- If freezing and thawing do increase the hydraulic conductivity of these cover and liner materials, how much protective soil cover is required to prevent freezing?
- What changes can be made in the design and construction technology for soil liner systems in cold regions that will reduce costs or improve productivity?
- What are the cost savings that the new technology will bring to soil liner systems in cold regions?

BACKGROUND

Over recent years, a considerable debate has developed regarding the effects of freezing and thawing on the hydraulic conductivity of the soil components used in landfill covers and liners. While laboratory test results have consistently indicated that freezing and thawing cause large increases in the hydraulic conductivity of compacted natural clay soils (e.g., Chamberlain et al. 1990, Kim and Daniel 1992, Bowders and McClelland 1993, Othman and Benson 1993), information from definitive field studies has not been available. Furthermore, the field evidence that is available is conflicting (e.g., Starke 1989, Paruvakat et al. 1990, Sowers 1993). These authors found some or no change in hydraulic conductivity from tests conducted on samples taken with thin-walled tubes. However, the laboratory evidence has been so convincing for compacted clay soils that regulations and guidelines have frequently required that compacted clay liners and covers be protected against freezing.

To protect a compacted clay cover from freezing, the normal method employs a thick layer of fill on top of the compacted clay layer. This fill layer has several functions. It provides a medium upon which to grow grass to control surface erosion; it provides a medium to keep the hydraulic barrier moist and prevent it from drying and desiccating; it acts as a barrier to ultraviolet light for geosynthetic components of the cover system; it acts as a barrier to burrowing animals; and it acts as an insulation layer to prevent freezing of the clay component of the cover system.

Only 1–2 ft (0.3–0.6 m) of fill soil is required as the protective cover in regions where frost is not a problem, the thickness primarily depending upon the type of grass used and the amount of precipitation. The thickness of the frost-protection fill layer is usually estimated and is often excessive because of uncertainties in the estimate. If the compacted clay does freeze, for instance during construction of a liner or cover or during an especially severe winter, regulatory rules typically require specific actions to show that there was no measurable frost damage. This issue has generated heated debate because several studies have shown that no damage was caused by freezing and thawing. However, Benson et al. (1994) and Chamberlain et al. (1990) (and this report) show clearly that the negative findings of frost damage are an artifact of the field sampling method. This report tells us that large increases in hydraulic conductivity are caused in compacted clay soils by freezing and thawing, and that the sampling and test methods are critical to accurately identifying these changes.

In contrast to the results for compacted clay, past laboratory testing of GCLs and sand–bentonite mixtures has shown that freeze–thaw has no deleterious effect on hydraulic conductivity. Several projects by Chen-Northern (1988), Geoservices (1989), and Nelson (1993), and more recent investigations by Kraus and Benson (1994), show a statistically significant decrease in hydraulic conductivity after freeze–thaw testing of three GCLs. However, since field verification of these results on GCLs and sand–bentonite mix-

tures are nonexistent, it was a purpose of this study to validate the past laboratory results in field test sections.

This report summarizes the research activities accomplished in this portion of the CPAR program.

TEST PROGRAM

Approach and test materials

To allow a comparison between field frozen samples and laboratory samples, a field test site was constructed at a landfill in Menominee Falls, Wisconsin. This site was selected because it was located in an area that was likely to freeze each winter, and materials and equipment were available that would allow full-scale construction techniques to be used. The site was the location of both a closed and an active landfill operated by Waste Management, Inc., for WMX, Inc., one of the partners in the CPAR project. Five compacted soil test pads (two each using two natural clays, and one using a sand–bentonite mixture), three ponds, each lined with a different GCL, and nine test pans containing GCLs (Fig. 1) were constructed at the landfill site.

Compacted clay

Two natural clay soils (Parkview clay—PV, and Valley Trail clay—VT) were selected for evaluation from four possible sources. Index properties and hydraulic conductivities were measured during preliminary evaluations. Parkview clay was selected because it has a relatively low plasticity index (LL = 31, PI = 17), while Valley Trail clay was selected because it had a higher plasticity index (LL = 45, PI = 27). The plasticity limits and other soil properties are given in Table 1. These two clay soils were similar to the types of compacted clay soil typically used in landfill

Table 1. Index properties for the compacted clay soils.

*Soil ID**	*USCS class.*	*Liquid limit*	*Plasticity index*	*Percent less than 4.8 mm*	*Percent fines less than 0.074 mm*	*Percent clay less than 0.02 mm*	*Optimum water content*	*Max. dry density* (lb/ft^3)	*Max. dry density* (kg/m^3)
PV	CL	1	17	100	80	20	13.7	117	1874
VT	CL-CH	45	27	100	97	35	18.0	111	1778
SB	SP	*ND	ND	100	14	9	16.0	108	1730

* PV—Parkview clay; VT—Valley Trail clay; SB—sand–bentonite; ND—not determined.

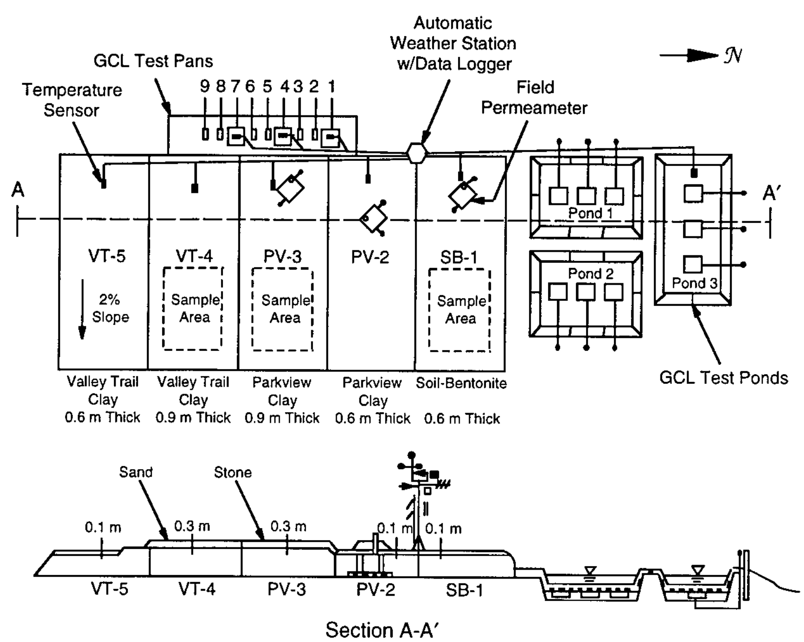


Figure 1. Plan view of the test site. Test pads containing Parkview clay are labeled PV. Test pads containing Valley Trail clay are labeled VT. The test pad containing sand–bentonite is labeled SB.

cover and liner systems. The Parkview clay is a glacial till deposited during the last glacial advance over southeast Wisconsin. It occurs in dense deposits at the test site and contains pebbles, cobbles, and occasional boulders. The Valley Trail clay is a glacio-lacustrine clay from east-central Wisconsin. It is varved and relatively free of large particles. Nearly all of the Valley Trail clay passes the no. 200 sieve (less than 0.074 mm), whereas only 80% passes for the Parkview clay. Compaction curves for these soils were developed using ASTM D698 procedures. The maximum dry unit weights for these soils are: Parkview clay—117 lb/ft^3 (1874 kg/m^3), and Valley Trail clay—111 lb/ft^3 (1778 kg/m^3). The optimum water contents for the Parkview and Valley Trail clays are 13.7 and 18.0%, respectively.

Sand–bentonite

The sand–bentonite (SB) mixture was prepared in the field so that it represented a typical sand–bentonite liner material. The base was a clean mortar sand purchased from a local concrete supplier. It was classified as poorly graded, clean, medium to fine sand (SP). More than 90% of the sand particles passed the no. 30 sieve (0.420 mm) and less than 5% passed the no. 200 sieve (0.074 mm). A granular sodium bentonite (American Colloid CS-50) with no polymer additives was used as the admixture to control hydraulic conductivity. The theory is that the bentonite, when well mixed with the sand, will hydrate on exposure to water to swell and block the flow of water through the continuous void paths in the sand. A target mixture containing 9% bentonite was selected on the basis of laboratory hydraulic conductivity tests. Compaction curves for the selected mixture indicate that the maximum dry unit weight is about 108 lb/ft^3 (1730 kg/m^3) and optimum water content is 16%. The index properties for the sand–bentonite (SB) mixture are given in Table 1.

The sand and bentonite were combined inside a mobile concrete mixing truck in an attempt to produce a homogeneous, uniform mixture. The mobile concrete mixer fed dry sand and bentonite at a controlled rate onto a belt to a mixing auger. Water was added as the dry materials were dropping into the auger. The auger was about 2.5 m long and encased by a rubber boot. The mixer worked well, but initial quality control (QC) tests showed that some of the mixture contained a lower percentage of bentonite than was desired. Bentonite aggregates appeared to collect and build up in the space between the auger and its protective cover. To correct for this problem, dry bentonite was added to the stockpile containing the lean sand–bentonite mixture to make up for bentonite stuck in the mixing machine. These components were blended on the ground with a loader bucket to create a homogeneous mix with the desired bentonite content. Unfortunately, additional QC testing after construction showed that, even with these efforts, the sand–bentonite mixture varied in bentonite content throughout the test section.

Geosynthetic clay liners

Three different GCLs (Claymax®, Bentomat®, Gundseal®) were used in this study. These GCL materials were provided by the CPAR partners. Each uses dry granular bentonite as the moisture barrier medium to prevent flow through the GCL. However, the geosynthetics used to contain the bentonite varied. Claymax and Bentomat each use two geotextiles whereas the Gundseal uses a single HDPE membrane. The backing materials for the Claymax and Bentomat GCLs are porous and they allow moisture to pass through to the bentonite. The bentonite in the Claymax and Bentomat is held in place in between the two geotextiles by cross stitching. The bentonite granules are bonded to the HDPE membrane in the Gundseal product, the membrane itself being a barrier to water flow. The Claymax and Bentomat GCLs function as barrier to moisture flow by allowing moisture to flow through the porous geotextiles to the bentonite. The bentonite clay then hydrates and swells, forming a putty-like filling between the two layers of geotextiles. This hydrated bentonite then forms the hydraulic barrier. In the Gundseal product, the HDPE membrane is the hydraulic barrier. The bentonite is there to ensure that the membrane does not leak should a hole or slit form during the manufacturing or construction process. Should a leak form in the membrane, the bentonite on the Gundseal GCL will hydrate and swell to form a moisture barrier.

All three of the GCLs come in long rolls that are rolled out on site by special equipment. The GCL sheets are overlapped during placement to provide a continuous barrier. Granular bentonite clay is placed in the overlap seam to prevent leaks from forming between adjacent sheets. Further description of these GCLs is provided by Estornell and Daniel (1992).

Test site description

Clay and sand bentonite test pads

Figure 1 shows the layout of the test site. Two test pads having thicknesses of 2 ft (0.6 m) (PV-2 and VT-5), and two test pads of 3-ft (1-m) thickness (PV-3 and VT-4) were constructed for each of the natural clays. One test pad having a 2-ft thickness was constructed using the sand–bentonite (SB-1).

The clay and sand–bentonite test pads were 30 × 70 ft (9 × 21 m) to allow the compaction equipment to achieve normal operating speed. This size was also selected because it reduced the chance that specimens to be collected would be affected by edge effects. Construction was completed in October 1992. The test pads were monitored until being removed in July 1994.

A layer of HDPE geomembrane was placed over the subgrade (2% slope) and then covered with a geocomposite drain (nonwoven geotextile on each side of a geonet). The geomembrane and geocomposite drain were used in the test pad permeameters. The HDPE also prevented water from migrating up into the test pads, and the drain allowed construction water and seepage to drain away from the bottom of the clay layer.

The natural clays were placed in 6-in.- (15-cm-) thick loose lifts spread with a Caterpillar D3 bulldozer and compacted with a Caterpillar 825 tamping foot compactor. The compactor pad feet were 6 in. long, which allowed them to fully penetrate the loose lift onto the previously compacted lift. This resulted in uniform compaction of the loose lift. The sand–bentonite was compacted with a vibrating compactor having a steel smooth wheel. Unit weight was measured with a nuclear moisture-density meter. Relative compaction exceeding 95% of the maximum dry unit weight (measured by ASTM D698 procedures) was attained on each test pad. The water content was 2 to 5% of optimum wetness.

Thicknesses of the test pads and the cover materials were varied to model different conditions and to permit partial or full penetration of frost. The 2-ft- (0.6-m-) thick test pads (SB-1, PV-2, and VT-5) were covered with a layer of 0.5-mil.- (0.13-mm-) thick polyethylene and 4 in. (10 cm) of sand to minimize desiccation. The 3-ft- (1-m-) thick Parkview test pad (PV-3) was covered with needle-punched nonwoven geotextile and a 141-in.- (3.5-m-) thick gravel layer to model a typical clay liner–leachate collection system used in Wisconsin. The 3-ft- (1-m-) thick Valley Trail test pad was covered with a 1-ft- (0.3-m-) thick layer of well-graded sand without a geosynthetic layer.

Field test-pad permeameters

Rigid-wall, in-situ field permeameters were designed and installed in test pads SB-1, PV-2, and PV-3 immediately after the pads were constructed in 1992. The permeameters were designed to allow testing of hydraulic conductivity in the full liner section after freeze–thaw. A key design element was that the testing should not disturb the soil structure created by the freezing and thawing process.

Figure 2 shows a section of the field permeameters. Construction consisted of carving soil away to leave an undisturbed 4- × 4-ft (1.3- × 1.3-m) block of clay or sand–bentonite. An HDPE box, open at top and bottom, was placed around the block of clay, then seamed at the bottom to the

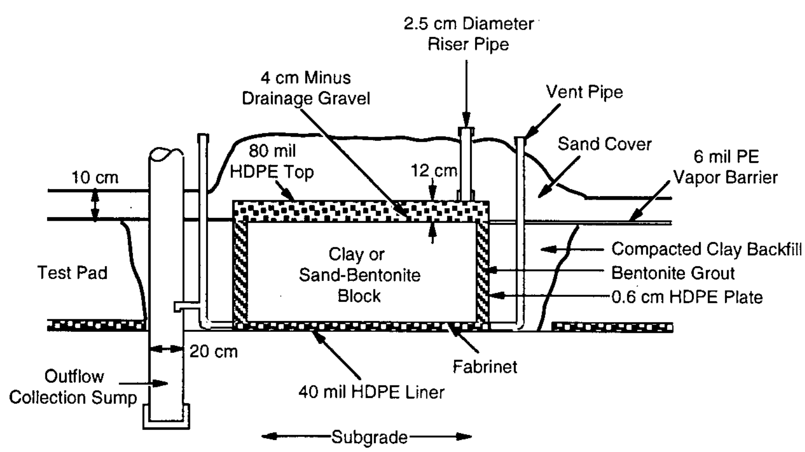


Figure 2. Details of the field permeameters in the test pads.

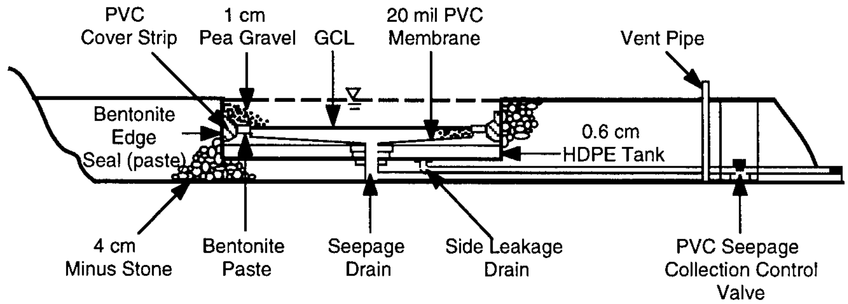


Figure 3. Details of the GCL test pans.

underlying HDPE. Piping and filter material were installed that connected to the geonet drain (placed below clay before compaction), thus allowing water that seeps through the block of clay to flow to a sump for observation and possible measurement. The 4-in. (10-cm) space between the block of clay and the inside wall of the HDPE box was filled with bentonite grout to prevent side leakage. A layer of nonwoven geotextile was placed on top of the clay and covered with a layer of coarse, 2-in. (5-cm) or smaller washed gravel that filled the space between the top of clay and the top of the HDPE box. An HDPE lid was placed and seamed on top of the box. A 1-in.- (2.5-cm-) diameter PVC riser pipe was placed at the high point of the lid to allow water to be added to the system and inflow of seepage to be measured.

During testing, the permeameters were covered with about 2 ft (0.6 m) of sand or gravel. This material was placed to hold the flexible HDPE lid in place so that uplift of the lid was prevented. Seepage was measured by filling the riser pipe until the water level stabilized, and then regularly monitoring water levels. In winter, the sand cover was reduced to 4 in. (10 cm) so that the cover over the permeameter was the same as that over the rest of the test pad.

GCL test-pans

Our goal during the GCL portion of the field investigations was to compare and investigate the hydraulic conductivity of the GCLs before and after winter. Three 32- × 13-ft (10- × 4-m) ponds, each lined with a different GCL under 10 in. (25 cm) of cover, were constructed during the fall of 1992 (Fig. 1). The ponds had underdrains beneath them. The goal was to measure the hydraulic conductivity after freezing and thawing. However, a flaw in the seepage measurement system prevented it from working as planned. The problem could not be corrected, so a different test system was designed and constructed in September 1993.

Nine test pans (Fig. 1) were constructed in three groups (one group for each GCL). Each group contained two sizes of test pans. Two test pans in a group had a surface area of about 8 ft^2 (0.75 m^2). The third test pan in each group had a surface area of 20 ft^2 (1.9 m^2). The large test pan and one of the small test pans in each group were used to test a GCL with a seam in the long dimension. The seams were made in accordance with the manufacturer's specifications. The other small test pan in each group contained a GCL with no seam.

The smaller test pans were commercially available HDPE storage pans. The larger ones were made by welding together pieces of HDPE plate stock (Fig. 3). A seepage collection system with drains was designed and constructed in each test pan and then covered with a GCL. Bentonite caulk and strips of plastic were used to prevent leakage along the sides of the GCL, which was then covered with about 10 in. (25 cm) of pea gravel to the top of the test pans.

The area surrounding the test pans was filled with gravel to the same level as that in the pans, so that freezing and thawing would be one-dimensional.

Water was initially added to the test pans to a depth of 1 in. (2.5 cm) over the GCLs to allow the bentonite to hydrate under low head conditions. After 1 week at the low head condition, more water was added. The test pans were allowed to hydrate under this condition for 1 month before we began collecting seepage data. The water level was kept relatively constant during the tests. Hydraulic gradients used in the field test pans ranged from 5 to 15 and averaged 10. The test pans were not drained for winter; they remained full of water. Water from a surface water pond located adjacent to the landfill was used as the permeant.

The seepage through the GCL and the seepage past the edge of the GCL were separated by the collection system. This was done so that water from a leaking edge seal would not be mistakenly included with seepage through the GCL. The flows

were separated using a sheet of PVC geomembrane that did not extend to the outer edge of the GCL (Fig. 3). The PVC captured water seeping through the GCL, but allowed water leaking through the edge seal to bypass the collection system and flow out through a different drain. The pea gravel beneath the PVC geomembrane was sloped to a drain pipe where the water was collected.

Hydraulic conductivity was measured through December 1993 until the water in the test pans began to freeze. Measurements were restarted in April 1994. On 3 June 1994, several of the test pans emitted a strong septic odor, indicating some amount of biological growth. About 1 L of chlorine bleach was added to each test pan in an attempt to reduce the biological growth and prevent clogging of the system. After the chlorine was added, it appeared that the closed collection system may have been limiting the amount of water that could seep through the GCLs. After identifying the potential problem, a change was made that allowed seepage to be collected in a way that ensured free drainage.

Electronic instrumentation

Forty temperature sensors and an automated weather station were installed to permit monitoring of freeze–thaw cycles, frost depths, and related climatic conditions. The data were collected every 5 minutes using a datalogger. Average hourly values were saved and transferred to a computer at the CRREL laboratory in New Hampshire via computer modem and cellular phone link.

Laboratory hydraulic conductivity testing program

Hydraulic conductivity tests were performed in the laboratory for comparison to measurements made using the field permeameters. Three types of permeameters were used in the laboratory testing: 1) the rigid-wall CRREL freeze–thaw permeameter (CRREL), 2) the conventional flexible-wall permeameter (CRREL and UW-Madison), and 3) a large-diameter flexible-wall permeameter (UW-Madison).

The CRREL rigid-wall freeze–thaw permeameter allows specimens to be frozen and thawed and tested for hydraulic conductivity. The freeze–thaw cycle can be repeated many times, freezing rates are controlled, and the freeze front moves vertically. The conventional flexible-wall permeameter tests were conducted on unfrozen specimens (diameter of 2.75 in. [7 cm]) following procedures described in ASTM D5084. The large-diameter flexible-wall permeameter was used to test specimens having a diameter of 12 in. (30 cm). Procedures in ASTM D5094 were used for tests in the larger-scale flexible-wall cell. Detailed descriptions of the equipment and test methods are provided by Chamberlain et al. (1990).

We did 12 laboratory freeze–thaw tests in the CRREL rigid-wall freeze–thaw permeameter (three each on the three soils, and one each on the GCLs). Specimens were prepared in the laboratory from samples taken from the site during construction. The clays were compacted in the laboratory to match field conditions, and placed in the CRREL freeze–thaw permeameter for testing. The confining pressure was maintained at 1 lb/in.^{2} (6.9 kPa), and the hydraulic gradient was maintained between 2 and 5 during freeze–thaw testing. The GCLs were tested in a similar manner.

Each specimen was subjected to 15 freeze–thaw cycles, with hydraulic conductivity being measured after the first, third, fifth, tenth, and fifteenth cycle. Following these freeze–thaw cycles, the Parkview and Valley Trail clays were tested after confining pressures were increased incrementally to see how this affected hydraulic conductivity.

Laboratory tests on field specimens of compacted clay

Hydraulic conductivity tests were also performed on large- and small-diameter unfrozen soil specimens. Specimens were removed from the field test pads before, during, and after the winter seasons of 1992–93 and 1993–94. Large-diameter specimens (Fig. 4) of thawed clay and sand–bentonite were removed from the test pads by hand carving 12-in.- (30-cm-) diameter soil blocks

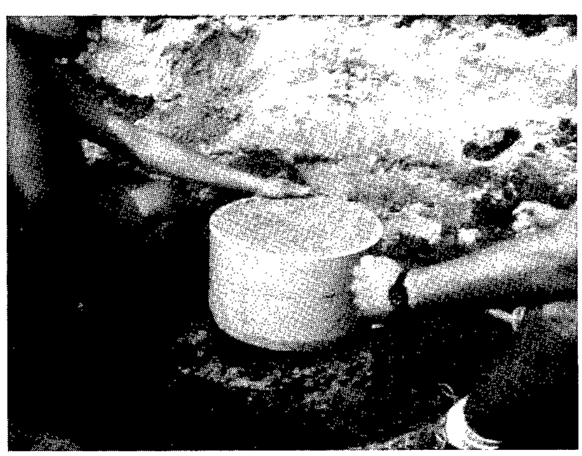


Figure 4. Taking a 12-in.- (30-cm-) diameter hydraulic conductivity test specimen from the field.

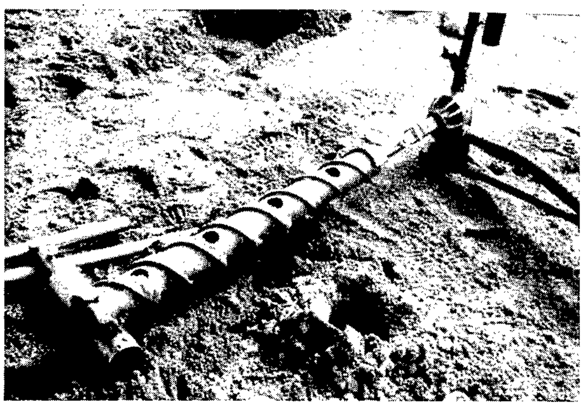


Figure 5. CRREL auger for taking a frozen core from the test pads.

before freezing in December 1992, and after the site thawed in the late spring 1993. Thin-wall tubes of 2.8 in. (7.1 cm) diameter were also pushed into the thawed test pads to collect specimens in June 1993. Benson et al. (1994) describe the sampling procedure in detail.

Hydraulic conductivity tests were also done on test specimens prepared from frozen cores that were collected from the sand–bentonite, Parkview clay, and Valley Trail clay test pads in March 1993 and March 1994. The frozen specimens were collected using a special rotary coring device (Fig. 5) developed by CRREL. The 2.8-in.-diameter frozen cores were packed and shipped frozen to the CRREL laboratory and maintained in a coldroom until they were prepared for testing. Benson et al. (1994) describe the sampling procedure in detail.

Analysis of soil structure

Thin sections were made of specimens of clay, sand–bentonite, and GCLs frozen in the laboratory and field. Thin slices, cut from frozen specimens with a band saw, were mounted on glass plates and milled thin to allow transmitted light to show through the included ice features. They were then photographed in a coldroom on a Polaroid camera light stage with both incident and transmitted light. In addition, scanning electron microscope (SEM) photographs were made of the test materials before and after freezing and thawing to examine the microstructure changes. Photographs were also made of the soil structure in the field after freezing and thawing in the pits from which the large-diameter field test samples were carved.

TEST RESULTS AND OBSERVATIONS

Temperatures

Temperatures at the site were monitored in the air and in the ground over two winters, 1992–93 and 1993–94, and recorded hourly. A typical air temperature plot is shown in Figure 6, and an example of a plot of the freeze and thaw depths during a winter is illustrated in Figure 7. Freeze–thaw cycling started in November of both winters. By mid- to late December, the freezing rate was steady. Frost reached the bottom of the test sections by mid- to late January and remained there for about a month. In mid-February, shallow, top-down freeze–thaw cycles started, and in mid- to late March, thawing began in earnest from both the bottom and top of the test pads. Thawing was complete by the first week of April in both winters. The test sections were frozen for about 3.5 months each winter. The freezing records for both winters show that, once freezing was established, little of the freeze–thaw cycling that occurred in the granular cover material reached the test materials.

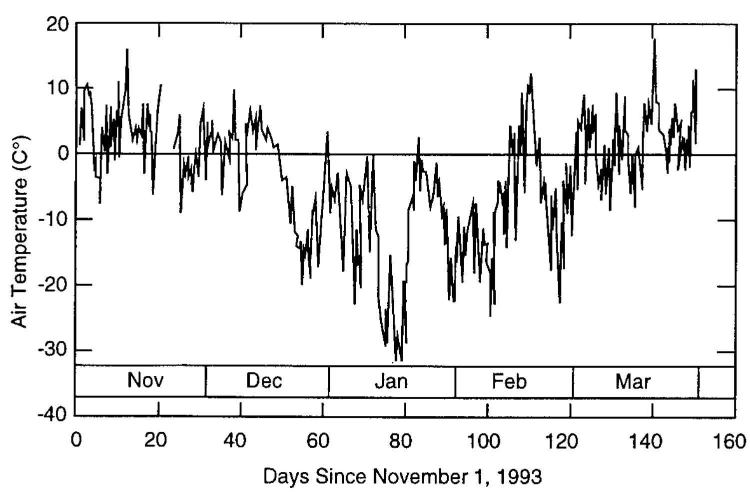


Figure 6. Air temperature record for the winter of 1993–94.

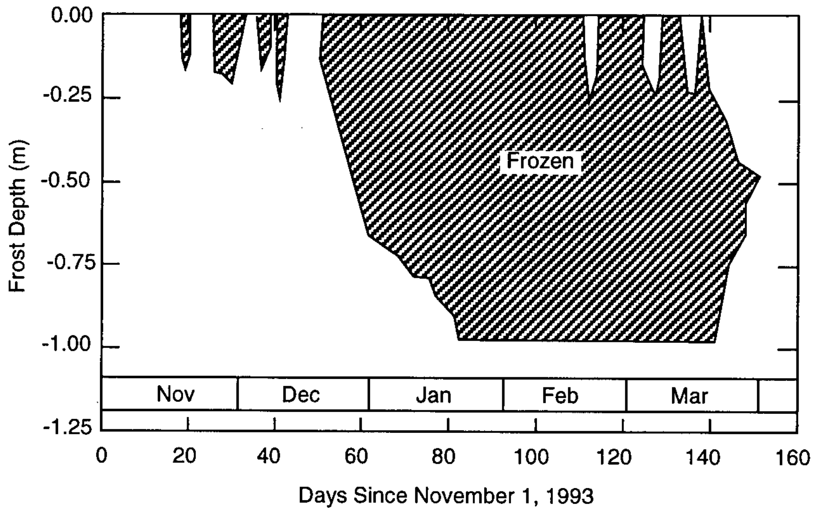


Figure 7. Example of the freeze and thaw depths during the winter of 1993–94.

Hydraulic conductivity of clays and sand–bentonite

Table 2 shows a summary of the average hydraulic conductivity measured for each material during different stages of the investigation.

Natural clay

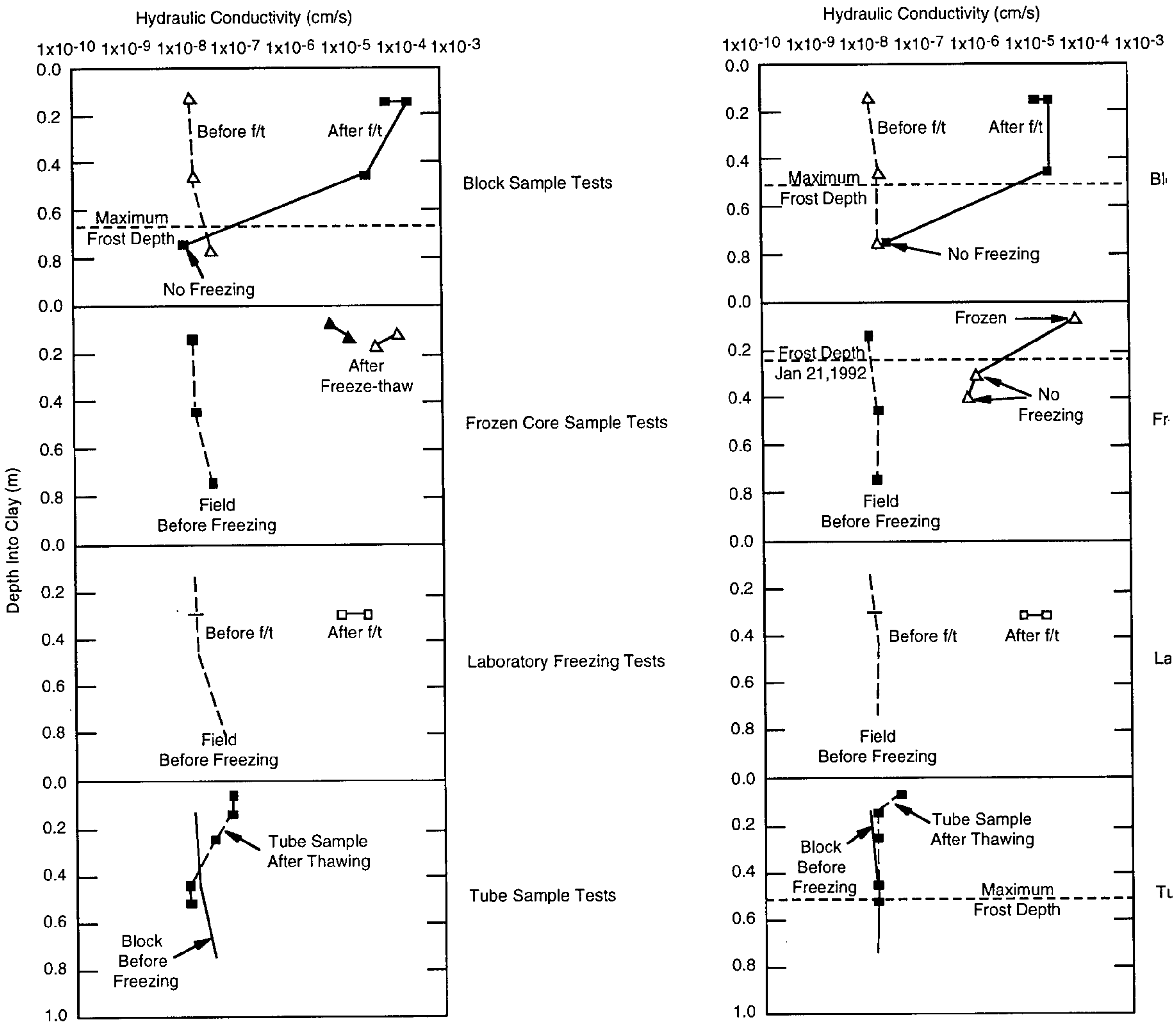
Comparisons of our laboratory and field tests on the two natural clays (Parkview clay and Valley Trail clay) show that freeze–thaw cycles caused an increase in hydraulic conductivity of three to four orders of magnitude (Table 2 and Fig. 8). The increase in hydraulic conductivity for the Parkview clay was from about 3×10^{-8} cm/s to greater than 1×10^{-4} cm/s. For the Valley Trail clay, the increase was from about 2×10^{-8} cm/s to about 8×10^{-5} cm/s.

This increase in hydraulic conductivity is attributed to the formation of cracks from ice lenses and shrinkage. Thin sections (Fig. 9) and half sections (Fig. 10) cut of these materials show the ice-filled cracks between aggregates of soil. A scanning electronic microscope (SEM) photograph (Fig. 11) shows further detail of a crack

Table 2. Summary of hydraulic conductivity measurements (cm/s) on the clay and sand–bentonite materials.

Test details	*Parkview clay (PV-3)*	*Valley Trail clay (VT-4)*	*Sand–bentonite (SB-1)*
CRREL laboratory (a) before breeze	2.3×10^{-8}	1×10^{-8}	$< 1 \times 10^{-8}$
UW laboratory before freeze (b)	3×10^{-8}	2×10^{-8}	1×10^{-8} (h)
CRREL laboratory (a) after 10 freeze–thaw cycles	1×10^{-5}	1.6×10^{-5}	$< 1 \times 10^{-8}$
Frozen core in CRREL laboratory (c) after thawing	5.3×10^{-5}	8×10^{-5}	Specimen piped
UW laboratory after 1 winter; upper 0.2 m (d)	1.4×10^{-4}	1×10^{-5}	Specimen piped
UW laboratory after 1 winter at 0.45 m depth (d)	4.5×10^{-5}	2.6×10^{-5}	Specimen piped
UW laboratory after 1 winter at 0.75 m depth (d)	2.5×10^{-8}	2.2×10^{-8}	Specimen piped
UW laboratory after 1 winter (thin-wall tube) (e)	3×10^{-8}	2×10^{-8}	Not sampled
Field test pad permeameter after 2 winters (f)	Could not read	Not tested	5×10^{-8}
CRREL laboratory tests with increased confining pressure (g)	6.9×10^{-7}	3.6×10^{-8}	Not tested

a 7-cm-diam. specimens prepared in the CRREL laboratory.
b 30-cm-diam. specimens carved from field test pads (Dec. 1992).
c 7-cm-diam. specimens taken from test pads by CRREL frozen soil coring device (March 1993).
d 30-cm-diam. specimens carved from field test pads (June 1993).
e 7-cm-diam. specimens taken from test pads with thin-wall steel tube (June 1993).
f Hydraulic conductivity of Parkview clay was so high after one winter season that the capacity for measuring seepage through the field permeameter was exceeded, therefore the hydraulic conductivity was not read.
g The hydraulic conductivity presented is after freeze–thaw with confining pressure increased to 70–75 kPa.
h This hydraulic conductivity k is from one of three specimens. The two other specimens appeared to have low bentonite content, showing hydraulic conductivities of 1×10^{-6} cm/s. They are not shown because of the piping.



a. Parkview clay.

b. Valley Trail clay.

Figure 8. Summary of hydraulic conductivity test results.

Figure 9. Thin section of a horizontal slice of frozen Valley Trail clay. Note thick ice features (white) in shrinkage cracks surrounding clay aggregates (black).

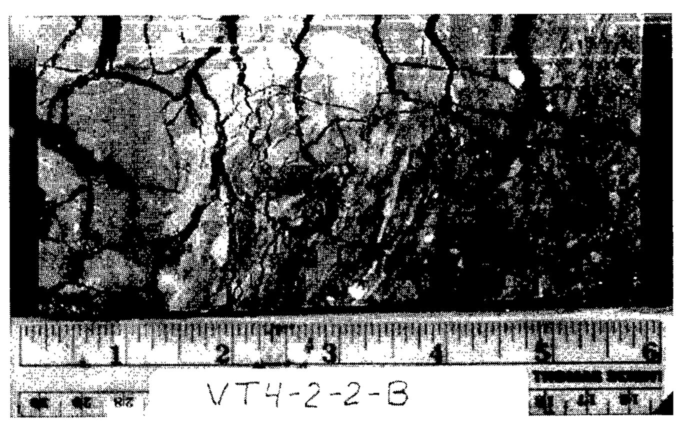


Figure 10. Vertical half section of Valley Trail frozen core. Note both ice-filled shrinkage cracks and ice lenses (black) surrounding clay aggregates (gray-white).

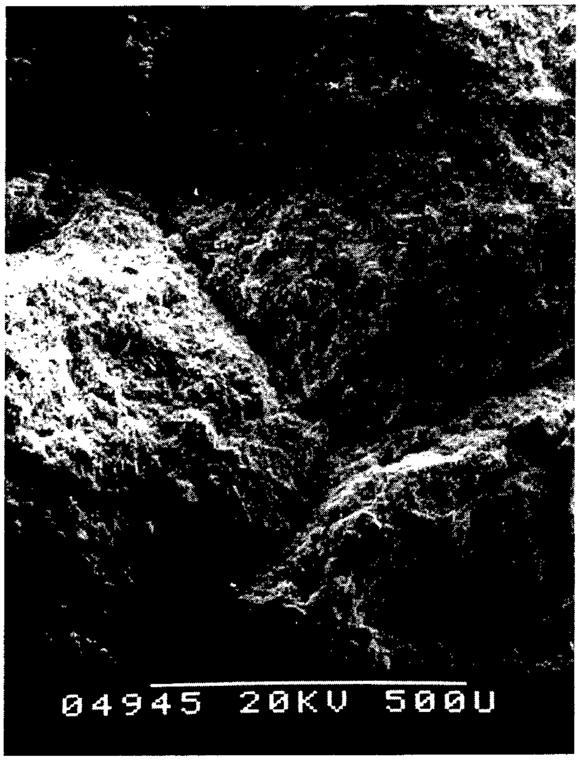


Figure 11. SEM photograph of a crack caused by freeze–thaw in Parkview clay.

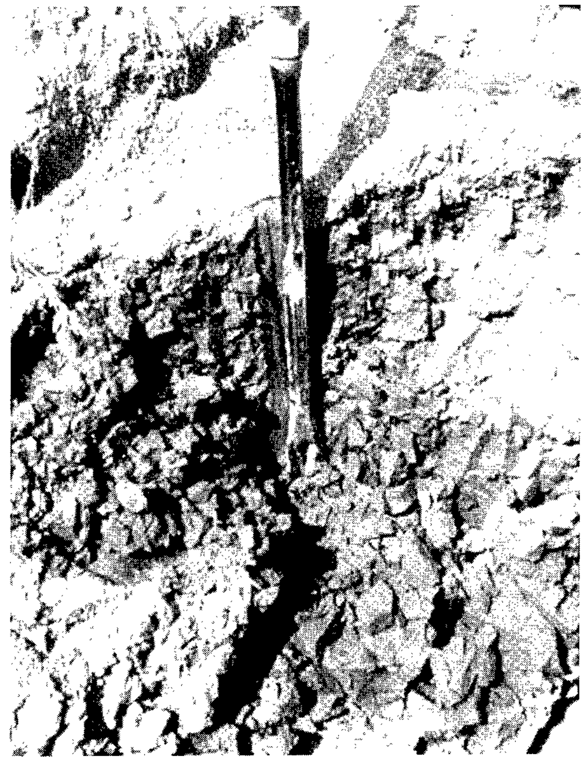


Figure 12. Test pit showing blocky soil structure caused by freeze–thaw cracking—Valley Trail test pad.

after thawing. Excavation in the test pads after thawing was complete exposed structures (Fig. 12) consisting of many block–aggregates, approximately 1 in.^{3} (1.6 cm^3) in size, separated by vertical and horizontal cracks.

We believe that the high hydraulic conductivities measured after freezing and thawing are representative of the field-scale hydraulic conductivities of the test pads. The test results obtained with the large-diameter samples and with the samples taken frozen agree very well (Fig. 8, top panels). Furthermore, the results of the laboratory freeze–thaw tests (Fig. 8, third panels) also agree very well with the results obtained with the field samples, making the laboratory test method a good way to predict field response of hydraulic conductivity to freezing and thawing.

However, the hydraulic conductivities determined from test specimens sampled with the thin-walled tube after freeze–thaw (Fig. 8, bottom panels) do not agree at all with the other field and laboratory test results. The values for hydraulic conductivity after freeze–thaw were not significantly changed from the values obtained before freezing and thawing. It appears that the pressing of the thin-walled tube sampler into the dense clay matrix increases the stress on the soil and causes the cracks to close. This explains why previous studies employing thin-walled tube samplers have drawn the conclusion that freezing and thawing does not affect the hydraulic conductivity of clay covers and liners. Benson et al. (1994) discuss these tests in detail.

To show this stress effect, hydraulic conductivity tests were also conducted on test specimens at higher stress levels than normally used in the back-pressure permeameter—i.e., at stress levels up to 10 lb/in.^{2} (69 kPa) in comparison with the 1 lb/in.^{2} (6.9 kPa) effective stress level normally used in our tests. Figure 13 shows that increasing stress decreases the hydraulic conductivity of the Parkview clay and that about 12 lb/in.^{2} (83 kPa) of stress is needed to decrease the hydraulic conductivity to its value before freezing.

The increasing stress test results also show where, in a landfill or hazardous waste site, freezing and thawing has its greatest impact. In covers, even with several feet of frost protection, the maximum effective stress will not generally exceed 3 or 4 lb/in.^{2} (21 or 28 kPa), whereas the stress level in a clay liner can easily exceed 12 lb/in.^{2} (83 kPa). The stress level in a cover will, thus, in most cases not be great enough to close the cracks and reduce the hydraulic conductivity to an acceptable value,

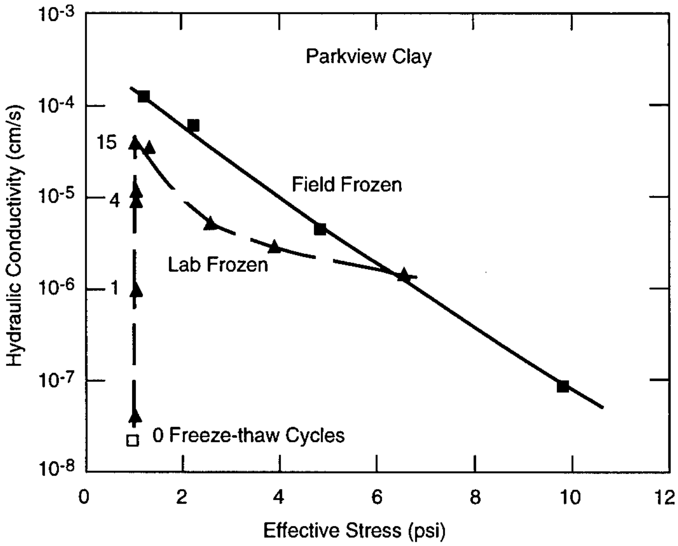


Figure 13. Impact of effective stress on the hydraulic conductivity of Parkview clay after freezing and thawing.

whereas in a liner, there can easily be sufficient overburden stress to close the cracks and reduce the hydraulic conductivity to an acceptable value. About 25 ft (7.6 m) of overlying soil and waste material would be required to close the cracks in a liner constructed with the Parkview and Valley Trail soils. This is an overburden readily achieved in most landfills, except at the margins.

The test specimens taken with the thin-wall sampling tubes after freezing and thawing had lower hydraulic conductivities than the block and core specimens. The hydraulic conductivities for these specimens were similar to the values existing before freezing (Table 2). One explanation for this difference is that a tube sampler disturbs the unique soil structure formed during freezing, the cutting and inside wall resistance that develops as the tube is pushed into the ground causing the increase in the stress on the sample. As was discussed in the previous paragraph, about 12 lb/in.^{2} of stress is needed to close the cracks in the clay soils examined in this project. For the tube samples taken from the Parkview and Valley Trail test pads, considerable stress was applied to cause the sampler to penetrate the compacted clay. Apparently, this stress is sufficient to close the cracks and reduce the hydraulic conductivity to the values existing before freezing. This was confirmed, as visual inspection of the samples removed from thin-wall sampling tubes did not reveal any of the usual blocky structure observed in the hand-carved large-diameter samples. These results and the effect of sampling technique are discussed further by Benson et al. (1994).

Test results from specimens that were taken from a region more than 1 ft (0.3 m) below the maximum frost depth in test pads PV-3 and VT-4 did not show any increases in hydraulic conductivity. Shrinkage cracks and ice lens cracks were not obviously present in the soil that was well below the reach of the frost zone and, therefore, an increase in hydraulic conductivity would not be expected. However, in the zone within 6 in. (15 cm) of the freezing front, the hydraulic conductivity was about 1×10^{-6} cm/s in the Valley Trail test section (Fig. 8). Thus, it appears that freezing affects the hydraulic conductivity some small distance below the freezing front. This is consistent with the prevailing ice-segregation theory that the shrinkage cracks are formed in the unfrozen soil beneath the freezing front because of the high moisture suction that develops there.

The effects of stress on crack closure led us to examine whether the damage to the clay material caused by freezing could be repaired in place without its being removed. Three passes of a rubber-tired scraper were made over the test pads to increase the stress level. Observations of the clay structure in the test pads made after the clay was remolded with the scraper showed that this apparently destroyed the blocky structure by compressing the shrinkage and ice lens cracks. Blocks caused by shrinkage cracks and ice lenses were not as visible.

Large-diameter blocks were carved from these samples in July 1994. Tests on large blocks removed from the remolded area showed that the hydraulic conductivity values obtained before freezing were nearly recovered.

Sand–bentonite

In contrast to the natural clay, comparisons of our laboratory and field tests on the sand–bentonite mixture showed no effect on hydraulic conductivity from freeze–thaw. The test results are shown in Table 2. The hydraulic conductivity measured in field test-pad permeameter SB-1 was less than 5×10^{-8} cm/s in June and July 1994 after two winter seasons. This is roughly the same as was measured in the CRREL laboratory tests (before and after freezing) on specimens prepared in the laboratory from sand–bentonite samples mixed in the field.

The sand–bentonite in test pad SB-1 showed none of the blocky structure that was present in

the natural clay test pads. Ice lenses and shrinkage cracks were not as prevalent as they were in cores from the natural clay test pads. The ice appeared just as crystals in the sand–bentonite matrix. Furthermore, excavations into the sand–bentonite test pad after thawing in both years revealed no blocky structure caused by ice lenses and shrinkage cracks, as was observed for the clay test sections.

Uniformity of the percentage of bentonite appeared to have a greater effect on hydraulic conductivity of the sand–bentonite than did freeze–thaw. Laboratory tests done at UW-Madison indicated that higher hydraulic conductivity in the large-diameter sand–bentonite specimens was caused by preferential flow through paths containing less bentonite. Piping (formation of channels) appeared in each of the UW-Madison tests and in some of the tests done in the CRREL laboratory.

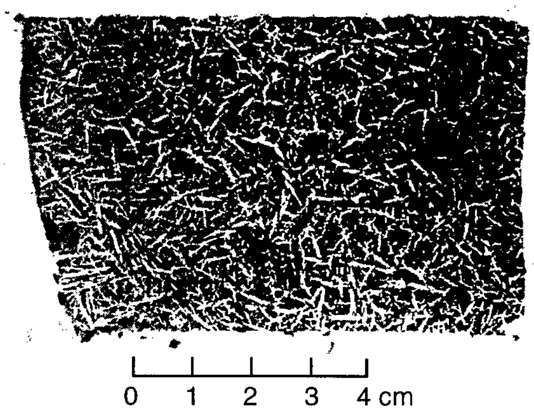
Additional observations of the sand–bentonite, after the field permeameter was disassembled, showed that the bentonite in the near-surface material had become soft and was wetter than that deeper in the section. Specimens removed from depths of 3, 5.5, and 8 in. (8, 14, and 20 cm) showed water contents of 42.1, 20.4, and 18.2%. The high water content at the surface is attributed to hydration of bentonite and swelling because of low confining pressure. This swelling also caused problems in doing the laboratory hydraulic conductivity tests. There was little or no flow of water through the test specimens because of the low effective stresses used and the continuous swelling of the sand–bentonite mixture. Since the determination of the hydraulic conductivity required the measurement of the flow of water both into and out of the test specimens, and since the flow rate of water was very slow for the low hydraulic conductivities measured, the swelling would mask the outflow and result in artificially high inflow rates. Thus, a considerable amount of time was required for the swelling to diminish and the inflow and outflow volumes to balance. Higher confining pressures than typically used (about 1 lb/in.^{2} [6.9 kPa]) in laboratory hydraulic conductivity tests would have reduce the swelling problem. However, the laboratory tests reported here intentionally used low confining pressures commensurate with those in the field tests.

Hydraulic conductivity of GCLs

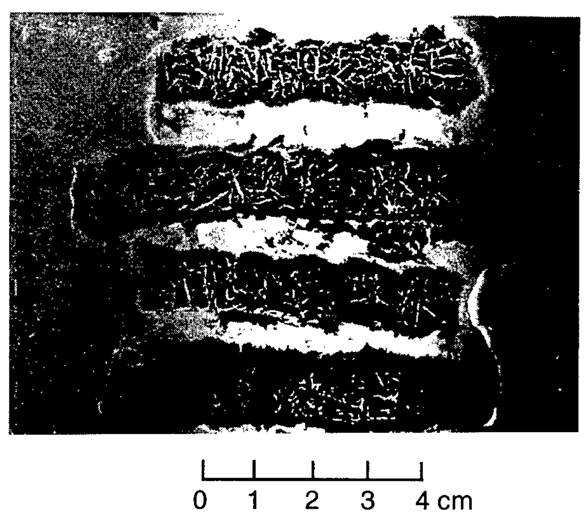
Laboratory test results

The laboratory test results on the GCL materials showed almost no change in the hydraulic conductivity from freezing and thawing. This was an interesting result, as the thin sections (examples in Fig. 14) showed many randomly oriented ice lenses surrounding aggregates of bentonite. In contrast to the low swelling characteristics of the Parkview and Valley Trail clays, the bentonite has a great affinity for water, even after freezing and thawing. The difference is attributable to the highly swelling nature of the "smechtite" clay mineral in bentonite and the relatively low swelling characteristics of the clay minerals in the compacted clay soils. This caused a reversal of the segregated structure formed during freezing of the GCLs and complete recovery of the hydrated structure that restricts the flow of water through the GCL systems.

The bentonite continued to hydrate under the low surcharge stress (1 lb/in.^{2} [6.9 kPa]) during the hydraulic conductivity tests, both before and after freezing and thawing. The swelling made the hydraulic conductivity determinations diffi-



a. Horizontal.



b. Vertical.

Figure 14. Thin sections of a frozen Bentomat GCL.

cult as water continued to flow into the test specimens from both the inflow and outflow burettes. Therefore, because of the long time required to wait for equilibrium to be established, only one freeze–thaw cycle was imposed on the GCL materials in the laboratory freeze–thaw tests. Nonetheless, it was apparent that freezing and thawing did not change the hydraulic conductivity of the GCL materials and that the hydraulic conductivity of the GCL test specimens was less than 1×10^{-8} cm/s, both before and after freezing and thawing for all three of the GCLs. These results were confirmed by tests conducted by Kraus and Benson (1994) on field frozen GCLs. As for the sand–bentonite test specimens, higher confining pressures than typically used (about 1 lb/in.^{2} [6.9 kPa]) in laboratory hydraulic conductivity tests would reduce the swelling problem. However, the laboratory tests reported here intentionally used low confining pressures commensurate with those in the field tests.

Field test pan results

As in the laboratory tests, the hydraulic conductivities (Table 3) of the GCLs in the field test pans also did not appear to significantly change after freezing and thawing. There are two exceptions. At the end of December 1993, the hydraulic conductivity in the nine test pans ranged from no measurable seepage from test pans 2, 4, 5, and 6, to a range of 9×10^{-9} to 4×10^{-8} cm/s from the remaining test pans. The average hydraulic conductivity was 1.4×10^{-8} cm/s for the test pans producing measurable seepage. In April 1994, six test pans produced measurable seepage (1, 2, 3, 7, 8, and 9). The hydraulic conductivity for those ranged from 1.2×10^{-8} to 3.5×10^{-8} to 4×10^{-7} cm/s. Test pans 4, 5, and 6 did not produce any measurable seepage. The test pan that produced the reading of 4×10^{-7} cm/s (test pan 7) was one of the larger pans with a seam. Excluding the results of that test pan, the average hydraulic conductivity in April 1994 was 2×10^{-8} cm/s. This slight increase in the average hydraulic conductivity may have been the result of freeze–thaw, it may be attributed to improvements in the method used to collect data, or it may be scatter that is within the level of accuracy of these measurements, or some other unknown factor.

Table 3. Summary of the hydraulic conductivity tests results in the GCL test pans. All tests were confined by approximately 0.25 m of pea gravel. Pea gravel was submerged; driving head equals 0.25 m.

Pan no.	*Specimen*	*Surface area (m^2)*	*Hydraulic conductivity before freeze, December 1993 (cm/s)*	*Hydraulic conductivity after freeze, April 1994 (cm/s)*
1	Bentomat*	1.8	1.5×10^{-8}	1.9×10^{-8}
2	Bentomat	0.64	NMSC†	1.0×10^{-8}
3	Bentomat*	0.65	1.0×10^{-8}	1.4×10^{-8}
4	Gundseal*	1.88	NMSC	NMSC
5	Gundseal*	0.65	NMSC	NMSC
6	Gundseal	0.65	NMSC	NMSC
7	Claymax*	1.88	2.8×10^{-8}	7×10^{-8}
8	Claymax	0.67	2.4×10^{-8}	2.8×10^{-8}
9	Claymax*	0.69	2.0×10^{-8}	3.0×10^{-8}

* Specimen included seam, full length of long axis. Dimensions for test pans 1, 4, and 7 were approximately 1.4 x 1.4 m. All other test pans were 0.6 x 1.2 m.

† No measurable seepage collected.

Test pan 7 produced the highest seepage of the nine test pans from the beginning of the test program. It contained a large specimen of Claymax with a seam. The hydraulic conductivity measured in test pan 7 in December 1993 was always the highest of the six, with a maximum measured value of 3.2×10^{-8} cm/s. In April 1994 the measured hydraulic conductivity was 4×10^{-7} cm/s. This high value could have been caused by a number of factors, including construction flaws (such as a poor seam), effects of freeze–thaw, or some other unknown cause. A clear cause of the increased seepage could not be identified during examination of the test pan after it was disassembled.

Test pan 2 produced the largest change in measured hydraulic conductivity before and after freezing. Test pan 2 contained Bentomat with no seam. It generated no measurable seepage before freezing in December 1993. However, in the spring of 1994, enough seepage was collected to indicate a hydraulic conductivity below 2×10^{-8} cm/s. It appears that into late December, after almost 2 months of soaking, the GCL material in test pan 2 was not fully hydrated, possibly as a result of the low surcharge. If the bentonite was continuing to hydrate during the hydraulic conductivity measurements in December, then outflow may have been limited to an immeasurable amount. After a season of freeze–thaw, the bentonite was likely fully hydrated, therefore allowing seepage.

In general the hydraulic conductivities measured in the field test pans were higher than those typically reported in the literature for GCLs undergoing laboratory tests. The root cause of this is unknown. However, we noted some differences

between the field tests and the typical laboratory tests that may have been contributing factors. One key difference was the confining pressure. In the field, a confining pressure less than 1 lb/in.^{2} (6.9 kPa) was produced by the thin (10 in. [25 cm]) layer of cover material. In the laboratory, 1 lb/in.^{2} of confining pressure or higher is often used. The lower confining pressure allows the bentonite to swell further and store more water in the double layers. With more swelling, there is a possibility that the porosity or free water is higher, thus a higher hydraulic conductivity might be expected. Another factor is the gradient. In the laboratory it is common to use a gradient as high as 75 for materials with a very low hydraulic conductivity. The field gradients ranged from 5 to 15. The higher gradient in the laboratory means that a large pressure differential exists across the specimen. This may serve to further confine or squeeze the specimen to keep it at a lower porosity and lower hydraulic conductivity.

Test pans 4, 5, and 6 contained the Gundseal GCL and did not produce any seepage in either the laboratory or the field. This is attributed to the HDPE geomembrane onto which the bentonite is fixed. The membrane prevents water from flowing through anything except the seams or a flaw in the HDPE. We included the Gundseal GCL in the study to see if freeze–thaw affected the bentonite in the seam. The two field test pan permeameters that contained the Gundseal GCL with seams did not leak. During disassembly of the pans, we observed that water had migrated a relatively short distance into the edge of the seam, but had not fully penetrated.

During June 1994 the hydraulic conductivity measured in the test pans increased dramatically to nearly 1×10^{-7} cm/s in the Bentomat GCL and Claymax GCL test pans. A visual characterization of the bentonite in the GCLs at the end of the field test showed a difference in structure from that seen in GCLs from the test ponds. Instead of being a homogeneous, plastic, flexible paste, the bentonite in the test pan GCLs was found to be almost brittle, as though the double layer had reduced. As a contrast, specimens of GCL removed from the three large test ponds constructed in 1992 did not show the brittle structure. The change in structure is different from that reported in the laboratory after freeze–thaw tests, so it may have been caused by some factor other than freeze–thaw.

One possible explanation for the change in structure may have been the addition of hydrogen chloride (bleach) to the test pans. The bleach was added to the test pans on 3 June 1994 to reduce biological growth. To examine this possibility, a free swell test was performed in the laboratory using granular bentonite, the pond water used in these tests, pond water with bleach added, Milwaukee city tap water, and tap water with bleach. The addition of bleach to the water in the free swell tests caused almost a 50% reduction in amount of swelling. This change was probably ascribable to the collapse of the double layer caused by adding the hydrogen chloride. It, thus, appears that the addition of bleach to the Bentomat and Claymax GCL test pans, to control biological growth, caused the large increase in the hydraulic conductivity observed in June of 1994.

Near the end of the field seepage tests, red dye was placed in the three large GCL test pans to see if preferential flow paths through the GCLs developed during the freezing and thawing and seepage processes. The dye appeared in the discharge water from the Claymax and Bentomat within 4 days. Water was not seeping through the Gundseal GCL, and the dye did not appear in its outflow collection pipe.

After draining the water from the test pans, we disassembled them and inspected them for clues to show where the water was flowing. The Claymax GCL test pan showed red dye staining throughout the bentonite section. This indicated that the water was passing through the entire section; no preferential flow paths developed. The bentonite in the Claymax GCL was hydrated, but it appeared less plastic than is usually seen in a GCL hydrated under such low confining pressure.

The Bentomat test pan showed red dye staining through part of the seam area when it was disassembled. This indicated that a preferential flow path existed and that water may not have been flowing at the higher rate through the entire section. As with the Claymax, the bentonite in this test pan did not appear to be as fully hydrated as is usually the case.

From the data collected in these field test pans, it is difficult to tell whether the higher-than-expected hydraulic conductivities were caused by freeze–thaw cycles, low confining pressures, low gradients, or other factors. Further large-scale field study is recommended to sort out the causes of the increases. The increases in the hydraulic conductivities of the GCLs in the test pans were relatively small, however, and are not considered consequential. The exception, of

course, is the increase caused by the chlorine bleach. The consequences of those results are important reminders of the care required in conducting tests on GCLs and in using them in landfills.

GCL field test pond test results

The three ponds constructed in 1992 did not have working seepage collection systems because of unrepairable leaks in the leachate collection systems. Nonetheless, some useful observations were made of how they held water. When constructed, each pond had a seam and a slice that was located over the seepage collection system. The slice was placed to investigate the effectiveness of self-healing of the bentonite in the GCL after freezing and thawing.

The slice in the Gundseal product allowed a high rate of seepage immediately upon filling of the pond. Initial attempts to fill the Gundseal GCL pond showed that it would not hold water. The sliced area was uncovered, and the slice was found to have widened from a slit to roughly 1.5 cm across. It appears that after the warm HDPE was buried and water was added, it cooled and subsequently contracted, causing the slice area to open, allowing water to seep out. A 10-cm-wide Gundseal GCL patch strip was placed over the slice, and the gravel cover was replaced. After the patch was placed, the pond retained water.

The pond lined with Bentomat GCL did not hold water soon after construction. We found that some seams were constructed without sufficient bentonite in the overlap. An attempt to excavate and repair the seams was made, but it was ineffective, and the pond continued to leak.

The Claymax GCL pond held water for the summer of 1993 (the summer after the first winter), but did not hold water after the second winter. A reason for this change could not be found.

The three GCL pond studies reveal some of the problems of conducting field studies with GCL barrier systems. Because the hydraulic conductivity of the hydrated GCL is so low, no leaks in the leachate collection system can be tolerated. Furthermore, these studies show the limitations of using the GCL systems under field conditions. Any imperfections in the seams or stress on cuts or defects can lead to significant leaks.

COST SAVINGS USING GCLs

Cost savings rationale

We have shown that the hydraulic conductivities of both GCLs and sand–bentonite mixtures, under ideal conditions in the laboratory and in the field, are not adversely affected by freezing and thawing. This is in sharp contrast to the behavior of compacted clay soils. Thus, there appears to be an advantage of using a GCL or a sand–bentonite mixture in place of a compacted clay in that much of the frost protection layer can be eliminated. However, the advantages of using sand–bentonite mixtures are not so great as using the GCL systems. With sand–bentonite mixtures, costs will be saved by eliminating the frost protection layer, but costs will also increase because bentonite clay and the bentonite with sand will have to be purchased. The sand–bentonite mixtures require 10 to 20 times as much bentonite as there is in a GCL system, and the mixture must be very uniform, as any regions of low bentonite content can be a path of low resistance for water flow. Thus, special equipment is needed to thoroughly mix the sand, bentonite, and water prior to its being compacted in place.

Thus, the advantage of using a GCL in place of a compacted clay soil is not just in the frost resistance, but it is also in the cost savings resulting from the elimination of much of the frost protection layer and from the increased storage capacity for waste material achieved. Geosynthetic clay liner systems can cost in place about the same as compacted clay liners, depending on the local price of compacted clay. Therefore, there may not be any savings in the hydraulic barrier itself. It is the experience of the second author (AEE) that a GCL liner may cost more or less in place than a compacted clay layer, generally a little more. So, for this discussion, we assume that the costs are the same.

With a GCL, all but about 1 ft (0.3 m) of the soil normally required for the frost protection layer can be eliminated. Some soil is still needed above the cover barrier as a medium to grow grass and to protect the GCL from mechanical and ultraviolet damage. This layer is still protective, but its primary enemy is not frost. The GCLs are also much thinner than the compacted clay layer for which they can be substituted: the hydrated GCL is about 0.5 in. (13 mm) thick and the normal compacted clay layer is 2 ft (0.6 m) thick. Figure 15 schematically illustrates the increased storage capacity gained by the elimination of the compacted clay and most of the frost protection layer.

Frost protection layer thickness required for a compacted clay barrier

We first determined how much frost protection is required over the U.S. We used a freezing index map from TM 5-818-2, *Pavement Design for Seasonal*

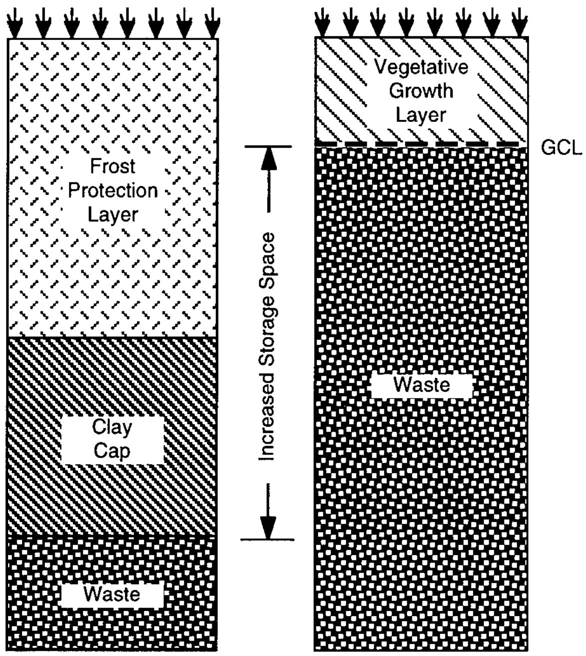


Figure 15. Increased storage space resulting from the use of a GCL and the elimination of the frost protection layer.

Frost Conditions (U.S. Army 1985), which shows contours of freezing index for the coldest year in 10 years of record or the 90th percentile (Fig. 3-1 and 3-2 in TM 5-818-2). Examination of longer records of freezing index data showed that using a 95th or greater percentile did not result in a significantly greater freezing index.

The thickness of frost protection required to prevent frost from penetrating into the hydraulic barrier was determined using the freezing index data in a frost depth model developed at CRREL (Aitken and Berg 1968). We assumed that a silt soil would be used as a frost protection layer, that the density of this layer would be about 110 lb/ft^3 (758 kPa), that the water content would be 17%, and that the surface would have a grass cover. The resulting map showing contours of equal frost protection layer thickness is given in Figure 16. It can be seen that the range of frost protection required is 1–6 ft (0.3–1.8 m) in the U.S., with anywhere between 1 and 3 ft (0.3 and 1 m) of frost protection being required over the highly populated northern regions of the U.S.

Calculation of potential cost savings using a GCL liner system

Cost of frost protection

We have calculated these potential cost savings for different regions of the U.S. Our calculations assume that only 1 ft (0.3 m) of cover soil is needed as the medium in which to grow grass and any remaining space gained by eliminating the frost protection layer can be used to store waste material. This means that only 1 ft of protective soil cover is required everywhere. This 1 ft of soil thickness could only be used if a shallow-rooted grass was the turf cover, and if there was assurance that burrowing animals would not be a problem. Our calculations also assume that all of the space gained by eliminating a compacted clay layer and using a GCL layer can be used to store waste material, the thickness of the GCL being insignificant. We assume that the cost of obtaining, excavating, hauling, placing, and compacting fill for a frost protection layer would cost \$10/yd^3 (\$13/m^3). That figure is an average for several projects at CH2M Hill.

Value of storage space

The value of the storage space gained by using a GCL in place of a compacted clay layer was estimated from data published by the National Solid Wastes Management Association (Repa 1990). Table 4 summarizes data taken from this report for five studies of landfills with clay or clay–composite cover systems. Only the early development, construction, closure, after-closure and other costs, such as interest on borrowed money and profit, are included in this cost estimate. The operating costs, which do not add value to the storage space, are not included. The lower right corner of Table 4 shows that the average value of the storage space for the five studies is about \$21/ton (\$19/tonne) of waste.

Calculation of cost savings

To calculate the cost savings achieved by using a GCL in place of a compacted clay liner, we assumed the cost of the frost protection layer to be \$10/yd^3 (\$13/m^3) and the value of the storage space to be \$21/ton (\$19/tonne) of waste. The density of the waste is assumed to be 40 lb/ft^3 (276 kPa). On an acre-foot basis, the cost of the frost protection then is about \$16,000/acre-ft (\$13/m^3) and the value of the waste fill space is about \$17,500/acre-ft (\$14/m^3).

The estimated resulting cost savings are given in Table 5 for the range of 1–6 ft (0.3–1.8 m) of frost protection. Under the fourth column heading, we can see that the cost savings attributable to the reduction in thickness of the protective cover ranges from \$0 across middle latitudes of America to \$80,000/acre (\$200,000/ha) in the north-central

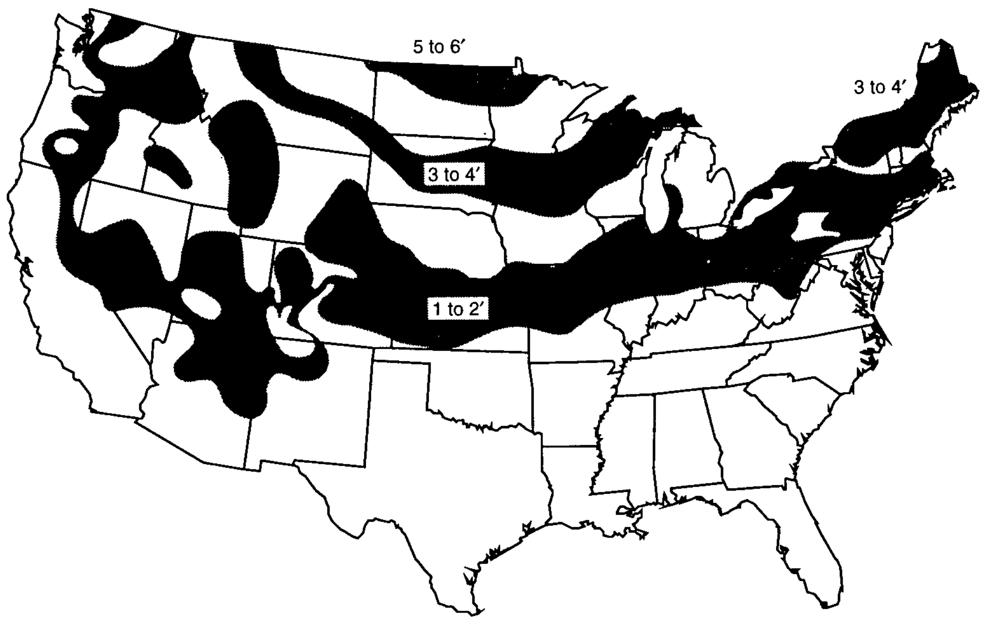


Figure 16. Thickness of protective soil layer required for compacted clay covers.

Table 4. Analysis of the value of waste storage space.

	Cost of storage space ($1000)					
Category	*Glebs* 1988a*	*Glebs* 1988b*	*SCS* 1989*	*SCS* 1990*	*Dell* 1989*	*Average for five studies*
Before development	2,785	592	7,260	6,681	891	3,642
Construction	8,728	5,690	25,565	77,910	4,171	24,413
Closure	2,475	147	2,452	9,777	1,315	3,233
After closure	9,120	1,835	5,526	5,526	7,500	5,901
Other†	7,150	407	69,949	119,369	0	39,375
Total fixed costs**	30,258	8,671	110,752	219,263	13,877	76,564
Capacity (million tons)	2.86	1.42	6	5.4	2.6	3.7
Capacity (10^9 kg)	2.59	1.29	5.4	4.9	2.4	3.4
Size (acres)	74	50	80	80	14.7	59.7
Size (ha)	30	20	32	32	5.9	24.2
Fixed costs ($/ton)	10.58	6.11	18.46	40.60	5.34	20.94
Fixed costs ($/tonne)	9.60	5.54	16.74	38.62	4.84	18.99
Fixed costs ($1000/acre)	409	173	1,384	2,741	944	1,282
Fixed costs ($1000/ha)	1,010	428	3,421	6,775	2,333	3,169

* From Repa (1990).
† Includes interest on debt, profit, etc.
** Excludes operating costs

Canadian border region. Under the fifth column heading is shown a cost savings of about $35,000/acre ($87,000/ha), attributable to the increased storage space caused by the reduction in thickness of the hydraulic barrier, even when there is no decrease in the thickness of the protective layer. Also under the fifth column heading in Table 5, we can see that, for the most northern part of the U.S., the cost savings attributable the increased storage space exceeds $70,000/acre ($173,000/ha) of landfill. The cost savings range from $35,000/acre ($87,000/ha) to $123,000/acre ($304,000/ha) for the region of the U.S. normally requiring 1–6 ft (0.3–1.8 m) of frost protection. Under the sixth column heading, we see that the total cost saving is greater than $100,000 in the populated regions of the northern States and that it can exceed $200,000/acre ($504,000/ha). Finally, under the last column heading it is shown that the cost savings for a 20-acre (8-ha) landfill can be $2,000,000 in a region just by eliminating 2 ft (0.6 m) of frost protection and using a GCL hydraulic barrier system in place of a compacted clay barrier.

The cost savings in terms of the total fixed costs

Table 5. Cost savings using GCL barriers.

Frost protection depth required w/o GCL (ft)	(m)	w/GCL (ft)	(m)	Decrease in frost protection thickness (ft)	(m)	Increase storage space (acre-ft)	(m^3)	Decrease in frost cover costs ($1000/acre)	($1000/ha)	Increase in value of waste storage space ($1000/acre)	($1000/ha)	Total cost savings using GCLs ($1000/acre)	($1000/ha)	Total cost savings for 20-acre site* ($M)
1	0.3	1	0.3	0	0	2	2500	0	0	35	87	35	87	0.7
2	0.6	1	0.3	1	0.3	3	3750	16	40	53	130	69	170	1.37
3	0.9	1	0.3	2	0.6	4	5000	32	80	70	173	102	253	2.04
4	1.2	1	0.3	3	0.9	5	6250	48	120	88	218	136	338	2.71
5	1.5	1	0.3	4	1.2	6	7500	64	160	105	260	169	420	3.38
6	1.8	1	0.3	5	1.5	7	8750	80	200	123	304	203	504	4.05

* 8 ha.

Table 6. Estimated cost savings by eliminating frost protection and using a GCL.

Thickness of frost protection layer eliminated (ft)	(m)	Cost savings using a GCL: Total costs* ($1000/acre)	($1000/ha)	Cost savings ($1000/acre)	($1000/ha)	Cost savings (%)
0	0	1282	3169	35	87	2.7
1	0.3	1282	3169	69	170	5.3
2	0.6	1282	3169	102	253	8.0
3	0.9	1282	3169	136	338	10.6
4	1.2	1282	3169	169	420	13.2
5	1.5	1282	3169	203	504	15.8

* Average for five studies.

for a waste disposal site give a better perspective of the potential impact of substituting a GCL system for a compacted clay layer. The average of all costs to build a landfill for the five studies analyzed from the Repa (1990) report is $1,282,000/acre ($3,169,000/ha) (Table 4). Table 6 shows that value added to a landfill by the increased storage space can be about 8 to 10% in the populated northern latitudes of the U.S., which have moderate to severe winters (regions normally requiring 2–3 ft [0.6–1 m] of frost protection).

TECHNOLOGY TRANSFER

The results of this study have been published and presented in a variety of venues (Appendix A). A standard method for conducting freeze–thaw hydraulic conductivity tests has been developed with input from the participants of this project.

CONCLUSIONS

The impact of this study on the design and construction of liner and cover systems is consequential. We have shown that freezing and thawing significantly increased the hydraulic conductivity of compacted clay soils, both in the laboratory and in the field. Hydraulic conductivity increased by three to four orders of magnitude for both of the natural clay soils used in this study. These increases are attributed to shrinkage cracks caused by freezing and to the formation of ice lenses. Such cracks were observed in the specimens frozen and thawed in the laboratory and the specimens removed from the test pads.

The damage caused by frost action may be repaired. Results from tests on frozen cores of clay removed from the test pads showed that increases in confining pressure caused a reduction in hydraulic conductivity. In two cases, an increase in confining pressure equivalent to the addition of 25 ft (7.6 m) of waste proved adequate to reduce the hydraulic conductivity to values less than 1×10^{-7} cm/s, the common regulatory target value. This stress level is readily achievable in a landfill liner, but not in a cover. In addition, it appears that the cracks formed by frost action may also be repaired in place by driving heavy equipment over the clay, provided that there is not a thick layer of protective cover soil on the thawed clay layer. This could be done before the clay is covered with waste or protective soil, but is not a practical solution once construction is completed.

This study has also shown that the hydraulic conductivity of sand–bentonite mixtures can be resistant to freeze–thaw if the sand is uniformly mixed with an adequate amount of bentonite. The hydraulic conductivity in the sand–bentonite test pad appeared to remain unchanged after two winters of freezing. The sand–bentonite test pad also showed no visible cracks. However, the performance of the sand–bentonite is very sensitive to incomplete mixing of its ingredients. Further study of the effect of freeze–thaw, with sufficient control to ensure uniform mixing of the sand and bentonite, should be undertaken. In addition, conditions that limit the problem of piping of bentonite should also be explored.

The test results show that the hydraulic conductivity of the GCL materials is also frost resistant, with hydraulic conductivities remaining below 1×10^{-8} cm/s after freezing and thawing. However, there is some uncertainty about the performance of seams, the sealing of construction damage (cuts), and the effects of the water quality on the hydration of the bentonite in the GCL materials. Additional large-scale field tests are needed to further examine these problems and to develop specific construction guidelines and methods for the use of GCLs.

The cost benefits of using GCL hydraulic barriers in place of compacted clay barriers are significant. These benefits result from the elimination of the soil required for frost protection above the hydraulic barrier and from the decrease of the thickness of the hydraulic barrier. The value added to a waste disposal site by substituting a GCL for a compacted clay layer can exceed \$200,000/acre (\$494,000/ha) or nearly 16% of the fixed costs of the disposal site.

Finally, this study has shown that the sampling and test methods are important for forensic analysis of frost damage to the hydraulic conductivity of compacted clay liners. The conventional thin-walled tube sampler is not acceptable for frost-damaged soils, as it compresses the soil and masks the damage. Furthermore, the hydraulic conductivity test cannot be done at high stress levels. The stress level must be commensurate with the in-situ stress. For a cover system, the maximum effective stress in the hydraulic conductivity test should not exceed 2 lb/in.^{2} (13.8 kPa).

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APPENDIX A: RESULTS FROM RESEARCH SUPPORTED BY CPAR FUNDING

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13. ABSTRACT (*Maximum 200 words*)

The common method of preventing the contamination of groundwater by landfills and hazardous waste is to encapsulate the waste material in a compacted clay liner and cover system. The frost resistance of compacted clay in landfills has been the subject of controversy for many years. Laboratory studies have frequently shown that freezing and thawing significantly increase the hydraulic conductivity of compacted clay soils. However, there has not been any corroborating field evidence. This study more closely examines this problem, and identifies cover and liner materials that would be frost resistant to increase construction productivity and save costs under a CPAR (Construction Productivity Advancement Research) cooperative agreement between CRREL and five private companies. The effects of freezing and thawing on the hydraulic conductivity of two compacted natural clay soils, one compacted sand–bentonite mixture, and three geosynthetic clay liners (GCLs) were examined. Both field and laboratory tests were performed on these materials. The field test site consisted of five test pads (four of clay and one of sand–bentonite), and nine test pans containing three different GCLs. Results showed that freeze–thaw caused large increases (greater than 1000×) in hydraulic conductivity in compacted natural clay, but little measurable change in hydraulic conductivity of the GCLs or the sand–bentonite mixture. GCLs and sand–bentonite mixtures are suitable frost resistant substitutes for compacted clay soils. Considerable cost savings can result if compacted clay soils are replaced with GCLs or sand–bentonite mixtures.

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